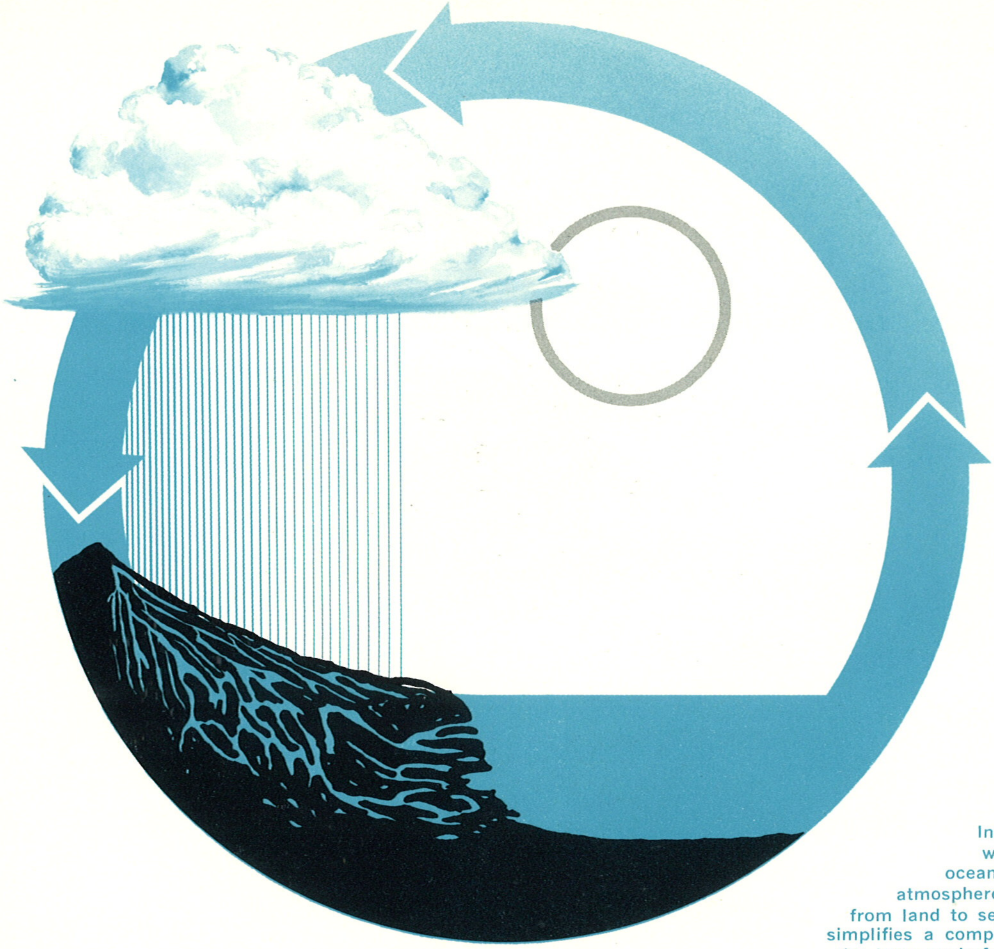
U.S. DEPARTMENT OF COMMERCE/Environmental Science Services Administration

THE HYDROLOGIC CYCLE



In an unending exchange, water is transferred from ocean to atmosphere, from atmosphere to land, and, finally, from land to sea. The diagram at left simplifies a complex cycle, showing only the large scale features of this exchange.

THE HYDROLOGIC CYCLE

Water is central to the history of man. His civilizations have persisted or disappeared as they have had enough, too much, or too little water. Man's history and mythology are marked by catastrophic floods and droughts and famine—and periods of plenty. But, until a century or so ago, our water-rich planet was rather sparsely populated, and only cataclysms seemed significant.

Water is central to our view today, but our emphasis has changed. We have grown more conscious of the steady growth of industry and population against our planet's fixed supply of water. The catastrophic changes in the supply of water described by earlier historians are less dramatic to us—and affected fewer people—than the 1965 and 1966 parching seasons of our northeastern states, or the seasonal flooding of our west and middle west. We are coming to understand that our prosperity and prospects for survival vary with the amount and distribution of fresh water and that each year there is no more water than before, but millions more of us. And we have learned through harsh experience how easily we can pollute or obstruct or diminish what water resources we have.

Despite our many lakes and rivers, the land we live on is the dry portion of our planet, slightly more than one quarter of the earth's surface. The land holds, in tiny reservoirs, the fresh water so essential to survival. But this is water in transition; its flow is toward the ocean where most of the earth's water is stored, most of it salt, most of it unfit for our consumption. To be accessible, useful, and abundant to us, water must be transformed from salt to fresh, and reservoirs on land must be constantly replenished by precipitation, most of which is formed from water evaporated from the sea.

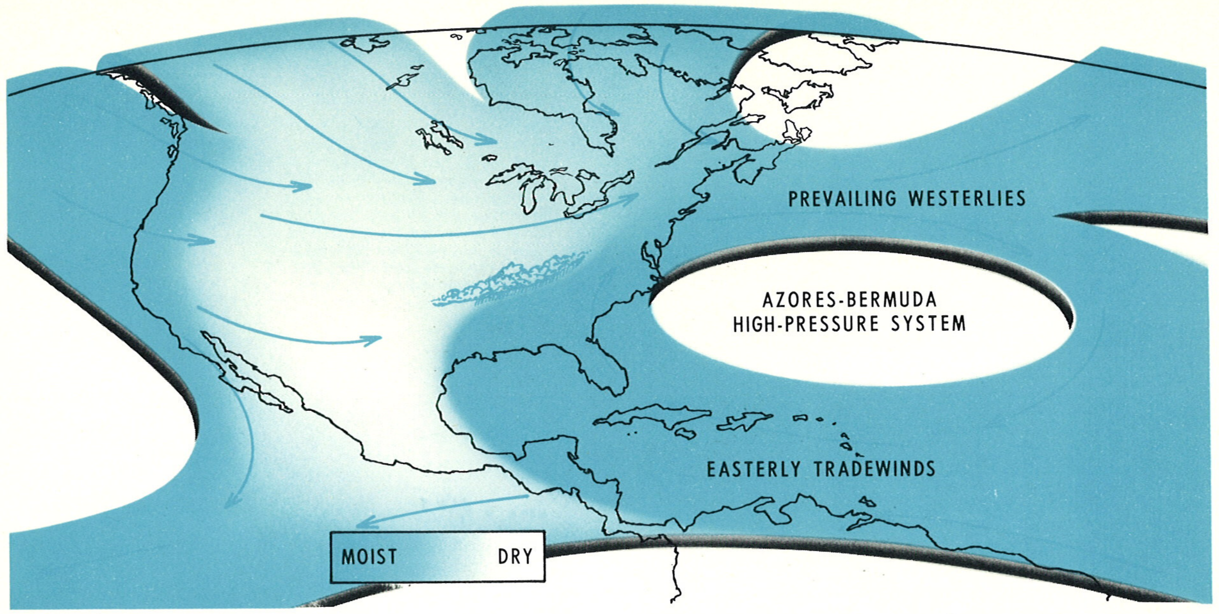
The transportation and distillation of water is accomplished by a continuous sequence which is part of a larger interaction between earth, sun, sea, and atmosphere. In a natural refining process that uses about one third of all solar energy reaching the earth's surface, some 10 million billion gallons of water are evaporated each year. About one-fifth of this comes from the land; the rest is from the sea. Evaporation—the process by which a liquid is transformed to the gaseous state—distills ocean water as it escapes as vapor into the atmosphere.

Atmospheric water vapor is transported to continents and islands, where lifting and cooling cause condensation—the opposite of evaporation—and precipitation in the form of liquid drops or frozen crystals. Ultimately, through runoff, evaporation, and other processes, the water brought to land is returned to the sea.

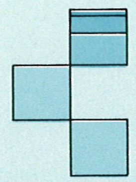
This continuous sequence, which affects the supply and distribution of water on land, is called the hydrologic cycle—the central feature of the science of hydrology.

Hydrology deals with the occurrence and distribution of water on land, its precipitation from the atmosphere, its storage, runoff, and evaporation, and its ultimate return to atmosphere and ocean. As it deals with the atmospheric and oceanic phases of the hydrologic cycle, hydrology is the cousin of meteorology and oceanography.

At ESSA, the Environmental Science Services Administration, hydrology contributes to the management of the Nation's available water, and to the improvement of man's ability to measure, forecast, and use the supply of water. Observations and measurements by hydrologists in ESSA's Weather Bureau inform the Nation of present and prospective water reserves, provide a basis for streamflow and flood warning information, and contribute to the public and economic health of heavily settled communities along our major rivers. As our population expands against an essentially fixed supply of water, hydrology becomes increasingly important in the management of this vital resource.



The hydrologic cycle occurs within the more general circulation of air masses over continents. In this idealized circulation pattern for North America, prevailing westerlies bring Pacific moisture to the seaward slopes of coastal mountain ranges, continue eastward to meet continental polar air over the plains states, and move out over the Atlantic, where moisture is recharged, and where part of the air mass is turned southward by the Bermuda High. Southeast of the continent, the transformed continental air joins maritime tropical air, and brings rainfall to the south and east of the country. The frontal line between continental polar (cP) air and maritime tropical (mT) air advances southward during the winter, northward in summer, driven by the warmth of the sun.



The world's supply of water: 97% in ocean, 2% in ice caps and glaciers, 0.6% in ground water, 0.3% in the atmosphere, 0.1% in lakes, inland seas and salt lakes, soil, and rivers.

Most atmospheric moisture comes from the sea, through a complex exchange of energy and matter between the ocean and atmosphere. Although the specific relationships in this boundary region are not wholly understood, it is clear that weather and climate over land areas are greatly influenced by variations in the interactions where air and water meet.

Emphasis upon the ocean as the primary source of precipitation in the hydrologic cycle is comparatively new. Formerly, it was held that about two-thirds of the continental precipitation came from transpiration (the process by which water in plants is transferred as water vapor to the atmosphere) and evaporation from water sources on land. More recently it has been observed that the dry air which most stimulates evaporation and transpiration over land tends to retain water vapor. As a result, some atmospheric water vapor gathered over the continent is returned to the ocean.

Orographic pre
A moist air
counters a
range and is f
ward, cooling
sufficiently to
precipitation. I
cade Mountain
Pacific northw
nual precipita
exceed 100 in
the mountains
move much of
ture from t
masses, produ
arid "rain sha
the lee side
range—a rain
which stretch
ward for hun
miles.

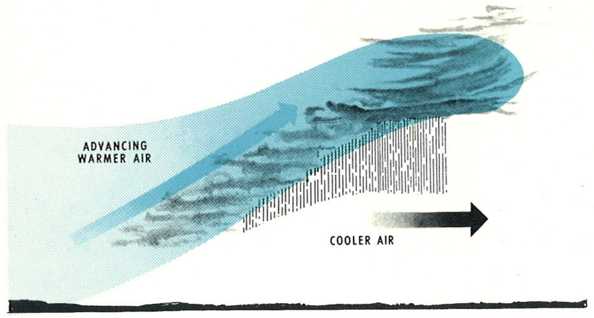
Frontal precipi
of air masses
characteristics
sities) is calle
denser air m
mountain ran
warm air upw
moist air co
precipitation o

It is in th
land that th
feature of
moves seaw
ture and fo
trajectory o
dry air dev
formed into
oped over la
The prev
hemisphere,
over the A
major proce
in the Unit
flows seawa
in its lower
Pacific air.
over the oce
the interact
phere's circ
moisture is

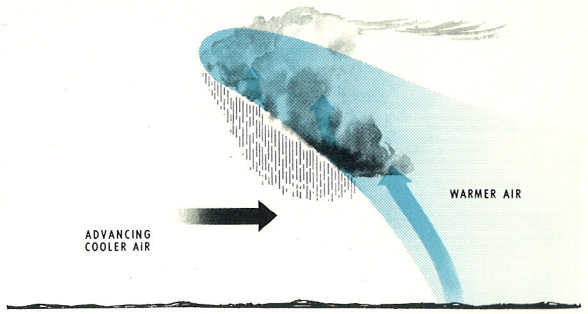
nce Services Administration

C CYCLE

Orographic precipitation. A moist air mass encounters a mountain range and is forced upward, cooling the air sufficiently to produce precipitation. In the Cascade Mountains of our Pacific northwest, annual precipitation may exceed 100 inches. But the mountains also remove much of the moisture from these air masses, producing the arid "rain shadow" on the lee side of the range—a rain shadow which stretches eastward for hundreds of miles.



Frontal precipitation. The interface of air masses of different thermal characteristics (and different densities) is called a front. The colder, denser air mass, like a coastal mountain range, forces incoming warm air upward. In rising, the moist air cools and warm-front precipitation occurs.



When a cold air mass overtakes a mass of moist warm air, a similar effect is produced. The cold air forces itself under the warm air like a wedge, forcing the warm air upward, and causing cold-front precipitation.

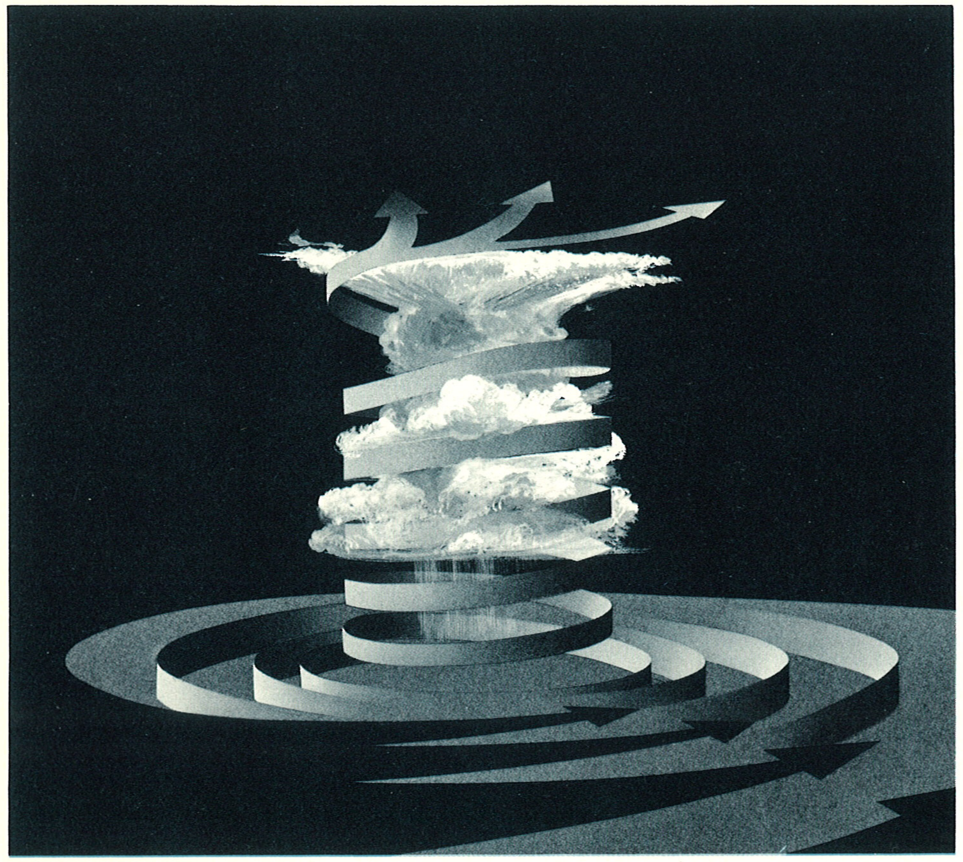
THE ATMOSPHERIC PHASE...

It is in the cycling of moisture between ocean and land that the hydrologic cycle appears as an integral feature of larger atmospheric circulations. As air moves seaward from the continents, it gains moisture and for the most part retains it. After sufficient trajectory over the ocean, continental air (relatively dry air developed over large land areas) is transformed into maritime air (relatively moist air developed over large water areas).

The prevailing westerly winds of the northern hemisphere, and semipermanent high pressure cells over the Atlantic and Pacific Oceans, control the major processes of this phase of the hydrologic cycle in the United States. The continental air of Asia flows seaward, receives a heavy charge of moisture in its lower layers, and is transformed into maritime Pacific air. Much of this moisture is precipitated over the ocean or returned to the Asian mainland by the interaction of persistent features of the atmosphere's circulation over the Pacific. Some of this moisture is shunted eastward and deposited along the seaward slopes of our Pacific coastal ranges.

The continental air formed over the northern portion of North America flows to the south and east, then out to sea, where it is transformed into moist maritime air. The Bermuda High, a high-pressure system centered near Bermuda, moves some of this air in a large clockwise sweep southward and out of the belt of prevailing westerly winds, and into the prevailing easterlies of the tropics. There, the transformed air masses are joined by moist maritime air swept northward from the tropics. Where this moist warm air encounters colder, dryer continental air, thermal differences produce our major storms, and bring much of the precipitation received by the United States east of the Rockies.

Regional processes are also at work in this atmospheric phase of the hydrologic cycle. Onshore winds bring moisture and precipitation to coastal areas and some precipitation is produced as air masses move across the continent. In some locations, seasonal differences between land and sea temperatures produce a monsoon cycle, the seasonal onshore winds which predominate in late spring and summer between large land and water masses at the lower latitudes. These bring a continuous flow of moisture-laden air inland from the warm oceans, and can produce large quantities of rainfall. Although most often associated with the southern coast of Asia, monsoon winds are present to some extent along our Gulf coast and the coast of the Mediterranean.



Convergence precipitation. Air near a low-pressure area tends to flow inward, and this net horizontal inflow forces air in the center of the area upward. If the inflow is strong enough to force air beyond saturation levels, precipitation occurs. Almost any atmospheric eddy (an element within a fluid mass that has an essentially independent life cycle) in which the flow of air at lower levels tends inward is likely to produce precipitation. Hurricanes, the largest phenomena of this type, produce very heavy rainfall through convergence and convection of moist air. Thunderstorm development and thunderstorm precipitation can be produced by such convergence also, as well as by heating from earth or sun, or convection forced by mountains or fronts. Although these small-scale storms cover only a few square miles, they generally occur in groups, and can yield intense bursts of rain over a period of several hours, effectively drenching a relatively large area.

...AND PRECIPITATION

Any particles of solid or liquid water that fall from the atmosphere and reach the ground are called precipitation, the link between the atmospheric and land phases of the hydrologic cycle. Precipitation has a variety of forms. In the United States, rain is by far the most common, with snow being next. Less common types are drizzle, hail, ice pellets, snow pellets, snow grains, and ice crystals. Although precipitation is formed from water vapor in the atmosphere, its formation depends upon certain other factors.

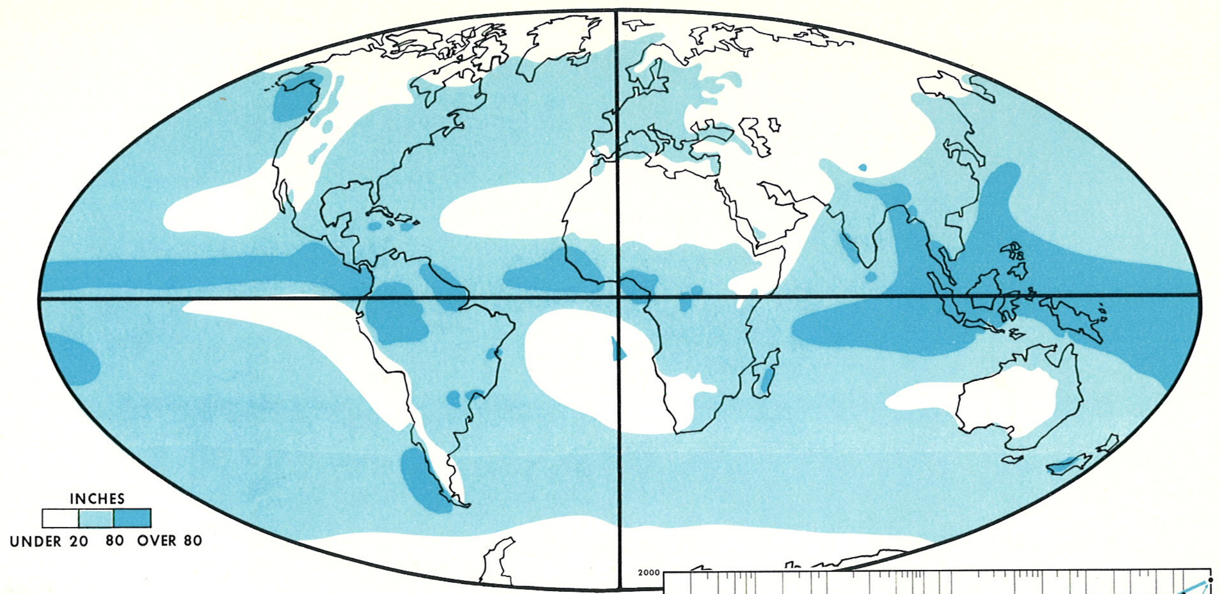
The amount of water vapor that can exist in any given space is a function of temperature: the warmer the air, the more active its molecules, and the greater its capacity for water vapor. When its capacity is reached, the air is said to be saturated. At 70° Fahrenheit (F), for example, a cubic yard of saturated air contains nearly four times the water vapor of the same air mass at 32°F. Thus, a mass of moist unsaturated air can become saturated if it is cooled sufficiently; and cooling much beyond saturation will cause the loss of some moisture.

The precipitation process begins with the formation of clouds, which are composed of water droplets or ice crystals, or both, formed by condensation (transition from vapor to liquid) or sublimation (transition from vapor to solid, or *vice versa*) of water vapor on certain nuclei. Smoke, dust, and sea salt particles are the most common condensation nuclei. Crystalline materials like silica and quartz provide sublimation nuclei on which water vapor is converted directly into ice crystals, bypassing the liquid state.

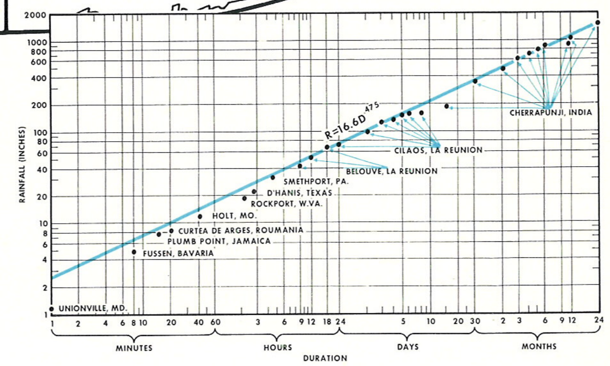
There is always some water vapor in the air, and there are always some condensation or sublimation nuclei, even on the fairest of days. Precipitation occurs when the air is cooled until it becomes saturated, condensation or sublimation takes place, and conditions favor the growth of cloud elements to precipitation size.

The only cooling that results in appreciable precipitation is produced by thermal or mechanical lifting. As the air rises, it expands, and expansion is accompanied by cooling. The mechanism involved in the cooling of air is often used to classify the precipitation. When meteorologists and hydrologists refer to frontal or orographic lifting, or to the ascent of air caused by the convergence of wind flow at low levels, they refer to different types of forced convection.

Air-mass precipitation is the term used to classify precipitation developed through convective overturning of atmospheric layers—a thermal process distinguished from the mechanical processes at work in forced convection. Convective overturning occurs in response to atmospheric instability, as when heavier cool air overrides lighter warm air. Relatively light rain or snow are the most common forms of air-mass precipitation, although heavy showers or thunderstorms are not infrequent.



Average annual rainfall is heavy along the low-pressure Equatorial belt, along the seaward slopes of coastal mountain ranges, and over the ocean. The continental interiors are comparatively dry, their moisture robbed by mountains or dispersed in the long journey of an air mass over land. Figures for the greatest point rainfalls observed are shown at right. Short-duration values are generally cloudbursts of the type encountered with thunderstorms. The Cherrapunji extremes were produced by monsoon rains.



THE LAND PHASE

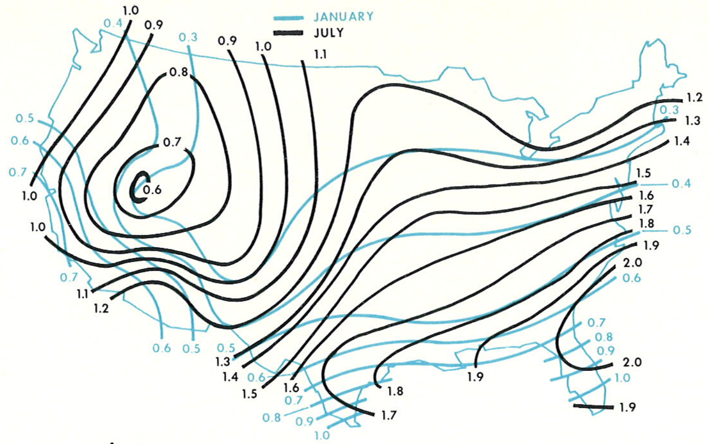
The amount of water vapor in the atmosphere is often expressed as the depth of precipitable water in inches—that is, the depth of liquid precipitation that would result from a column of moist air if all the water vapor in the column were suddenly condensed and precipitated. On the average, summer (July) precipitable water is about twice winter (January) precipitable water. No complete survey of maximum values has been made, but it is doubtful that the maximum total depth of precipitable water above any point in the United States has ever exceeded 3.5 inches.

But no natural process will remove all moisture from the atmosphere. Expression of atmospheric moisture as precipitable water reflects our point of view; most of our interest in the hydrologic cycle relates to the depletion and replenishment of the water resources of the land.

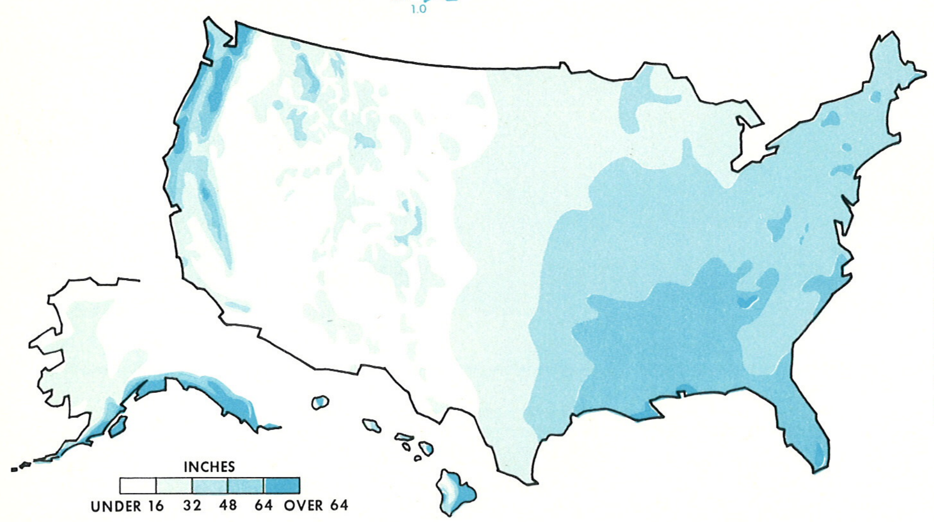
The essence of hydrology as a science is in measuring each phase of the terrestrial portion of the hydrologic cycle and in understanding the many physical processes through which the water goes. The practical concern with the hydrologic cycle, of course, is not with the cycle itself but with its variations. Precipitation does not occur uniformly throughout the world—there are normally dry and normally wet places. At any given point, there are important variations from year to year, season to season, hour to hour; and there are the more general excesses of flood and drought. The hydrologic cycle is as variable as the media through which it turns—the air-sea interface, the atmosphere, the surface and intricate internal structure of the land.

From rainfall, snowfall, and other forms of precipitation over the continents, water accumulates temporarily on vegetation, on the soil, and in lakes and rivers. As rain continues and as snow melts, water percolates into the soil. Some of this soil water is tapped by the root systems of plants, some seeps directly into streams and lakes, and some penetrates down to groundwater—the subterranean reservoir that feeds springs, keeps streams flowing between rains, and supplies wells. When the soil surface is absorbing water as fast as it can and still more rain falls, the additional water flows over the land surface and runs directly into lakes and streams. Flowing from small to larger courses, the water finally returns to the ocean or to continental sinks (like the Great Salt Lake) where evaporation balances inflow.

Annual rainfall in the conterminous United States ranges from less than 4 inches in the desert regions of the Southwest to more than 100 inches in the Cascade Range of Washington and Oregon. The average annual rainfall for the 48 states is about 26 inches. Snow and other frozen forms add about 4 inches more when melted, making a total annual average precipitation of 30 inches. Significant variations from this figure are infrequent, for there is rarely a day when rain or snow does not fall somewhere in the United States, and rarely a condition in which dry weather at one location is not compensated by wet weather somewhere else.



Mean January and July values for the atmospheric column from the surface to 8 kilometers (about 5 miles) show the seasonal effect on precipitable water — the amount of precipitation that would result if all the moisture in the atmospheric column were condensed and fell as rain.



Normal annual precipitation (in inches) for the United States is the general distribution of moisture in our country. Some of the specifics of this distribution are shown in the accompanying graphs and tables.

Of the 30 inches of average annual precipitation, 21.5 are evaporated or transpired by vegetation or evaporated from inland lakes and rivers, and 8.5 are runoff into rivers. About 3.0 of the 8.5 inches of runoff come through the large groundwater reservoir. The remaining 5.5 inches are direct surface runoff and runoff through upper layers of the soil; how much of each is difficult to determine. The runoff average of 8.5 inches varies between 5 and 12 inches, being nearly as variable as annual precipitation, and proportionately far more so.

Most of the variation in soil moisture occurs in the top foot, where in the eastern United States the fluctuations range typically from about 5 inches in early spring to less than one inch average thickness of water layer late in the fall. These fluctuations affect streamflow, groundwater recharge, and evaporation and transpiration.

Hydrologists are concerned with measuring present variations in the hydrologic cycle, and interpreting these observations with an eye toward anticipating future variations in the cycle. In this case, as in the case of many natural events, history is the best predictor. To determine how hard it can rain, hydrologists must know how hard it has rained in the past.

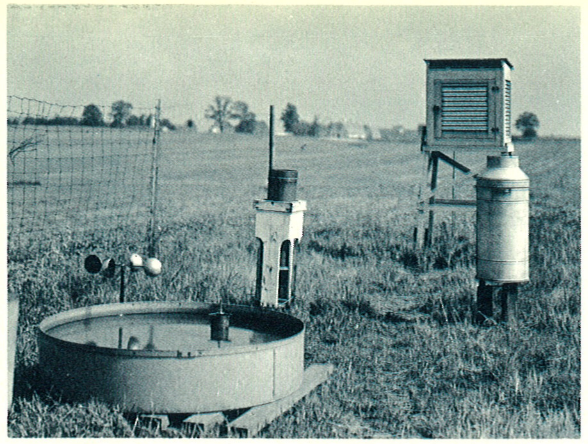
A vital history . . .

The history of precipitation in the United States is the accumulated records of thousands of precipitation gages. A network of more than 13,000 precipitation gages measures rain and snow. About 3,000 of these are recording gages, which weigh precipitation falling into a receptacle and record accumulated precipitation depth with time, permitting determination of intensities. In remote or seasonally inaccessible areas, storage gages are used whose capacity is sufficient to permit monthly or seasonal maintenance. Radar estimates of storm precipitation supplement gage network data. Aircraft and satellite reconnaissance is being used increasingly to measure the extent of snow cover, information essential in forecasting runoff caused by spring melting. Information from all these sources is used in ESSA's flood forecasting service in major river basins.

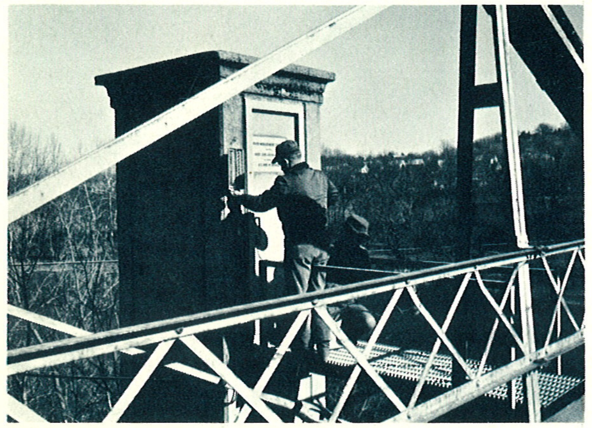
Evaporation is measured with evaporation pans at more than 300 stations equipped with anemometers to measure wind movement and maximum-minimum thermometers to measure air and water temperatures. Wind and temperature information helps relate evaporation from pans to evaporation from lakes and reservoirs.

Though useful to hydrologists, the record provided by precipitation gages is an imperfect history Heavy rains often occur over areas of only a few square miles, and the chance that the most intense rainfall will center over a gage is extremely poor. Many heavy rainfall regions have few or no gages.

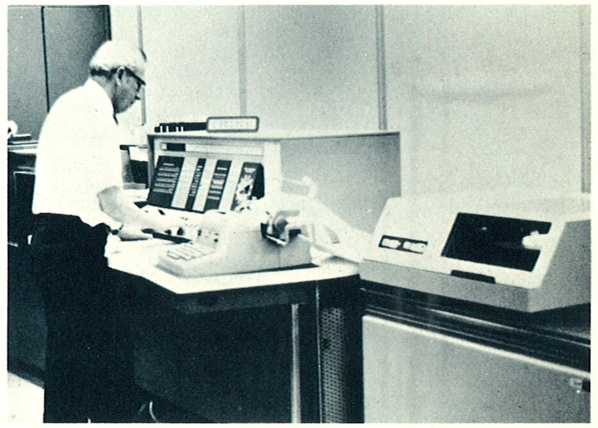
Snowfall records are even less complete. The heaviest snowfalls generally occur in mountainous areas difficult to reach. The high winds of blizzards cause



Clustered instruments wait to measure rainfall. The evaporation pan in left foreground is equipped with an anemometer and thermometer. Behind the pan, two rain gages are installed; gage at right automatically weighs and records accumulated precipitation. A standard instrument shelter in background houses instruments to measure temperature and humidity.



Telemetering equipment monitors the height of the Shenandoah River, part of ESSA's nationwide flood watch. Flood forecasts are based on data transmitted over telephone circuits to ESSA hydrologists. Credit: Western Electric



Precipitation and river data fed into computers are the basis for river and flood forecasts.

drifting, which makes accurate measurement of snowfall almost impossible.

Nevertheless, the precipitation record is important statistically, and has provided hydrologists with the means of anticipating destructive floods, drought, and trends in water resources. It is information needed by commerce along inland waterways, and in the design and construction of waterways and floodgates, bridges and highways, reservoirs and sewer systems. It is essential in managing water resources, as in monitoring evaporation of reservoirs and in limiting the discharge of pollutants into streams and rivers.

. . . to improve man's prospects for survival

ESSA's hydrologic services are felt in many ways, by many organizations, by many individuals. But it is when these services preserve life and property against extremes of the hydrologic cycle that their benefits are most vividly apparent.

Through its Weather Bureau, ESSA keeps a round-the-clock, round-the-calendar watch on the Nation's rivers. A special river and rainfall reporting network continually provides river and rainfall data for the preparation of river forecasts and flood warnings. This flood warning service is integral to ESSA's natural hazards warning program, which provides timely warnings of atmospheric hazards like hurricanes, tornadoes, and other severe storms, and of earthquake-generated seismic sea waves, or tsunamis. As with the other warning services, ESSA's flood warnings offer time—time to evacuate low-lying areas, time to move property and livestock to higher ground, time to take necessary emergency action. This service saves annually more than $100 million in flood losses—and an untold number of lives.

Hydrologists, with meteorologists and oceanographers, are learning more about man's influence on the hydrologic cycle, and more about the benefits and penalties which the cycle's variations bring to man. Through new knowledge and a new technology of earth satellites, computers, high-speed communications, and weather radar, they are improving man's ability to prevail in the face of natural hazards. And their work will help ensure that future generations are not left an arid planet, or networks of polluted streams.

U.S. DEPARTMENT OF COMMERCE · ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION

essa

ESSA/PI 670003 JUNE 1967 For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402

Price 15 cents

U. S. GOVERNMENT PRINTING OFFICE : 1967 O - 267-190